Accretion-Ejection Instability:
Quasi-Periodic Oscillation and *Jet*

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Summary

I. Introduction

II. Presentation of the Accretion-Ejection Instability (AEI)

III. Microquasars: accretion, ejection and QPO

IV. AEI and observations

V. Conclusions and present work

disk-jet connection

The accretion phenomenon is present in many systems: young stellar object, active galactic nuclei, x-ray binaries

➔ objects known to emit jets.

Accretion: to extract the energy and angular momentum from the inner part

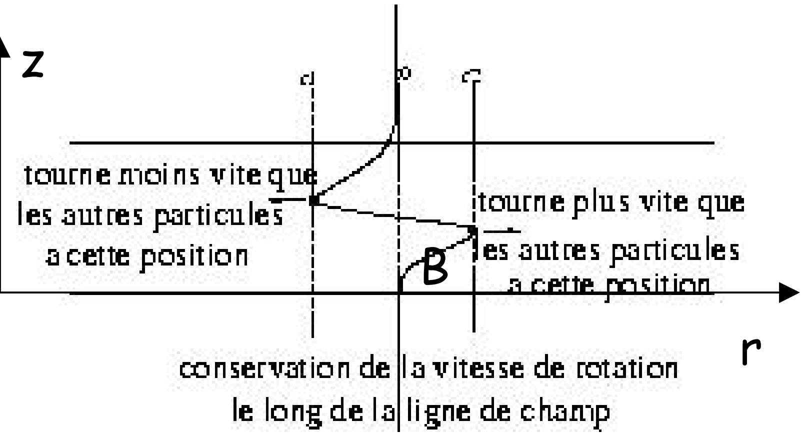
⇨ α disk model of Shakura & Sunyaev 73. radial transfert of angular momentum through trubulent viscosity

Ejection: origin and structure of the jets

⇨ MHD model (Blandford & Payne, Pelletier & Pudritz, ...): efficient way to extract energy and angular momentum from the disk

Magnetic Instabilities

Magneto-Rotationnal Instability (MRI) disque: Balbus & Hawley, 1991):



The Rayleigh criteria $\partial_r (r^2\Omega)^2 < 0$ becames in presence of magnetic field $\partial_r (\Omega^2) < 0$

⇨ always verified in the case of Keplerian disk

Energy to bend the field line

⇨ weak magnetic field ($\beta = 8\pi p / B^2 > 1$)

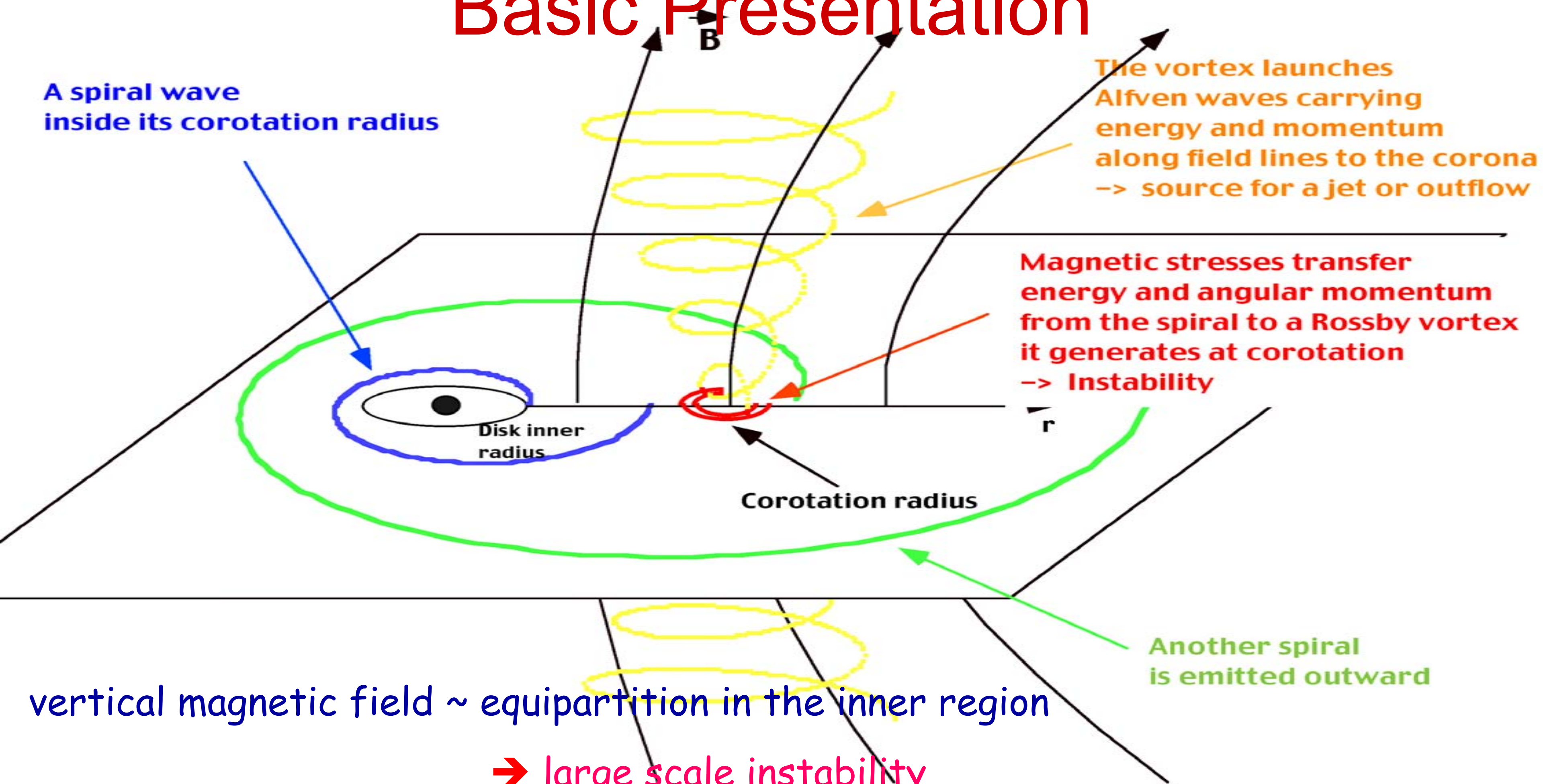
Accretion-Ejection Instability (AEI): it develops for $\beta \approx 1$ in the inner region of the disk and link accretion in the disk with ejection.

⇨ large scale coherente structure: Quasi-Periodic Oscillation (QPO)

II. Presentation of the

Accretion-Ejection Instability

Basic Presentation



vertical magnetic field ~ equipartition in the inner region

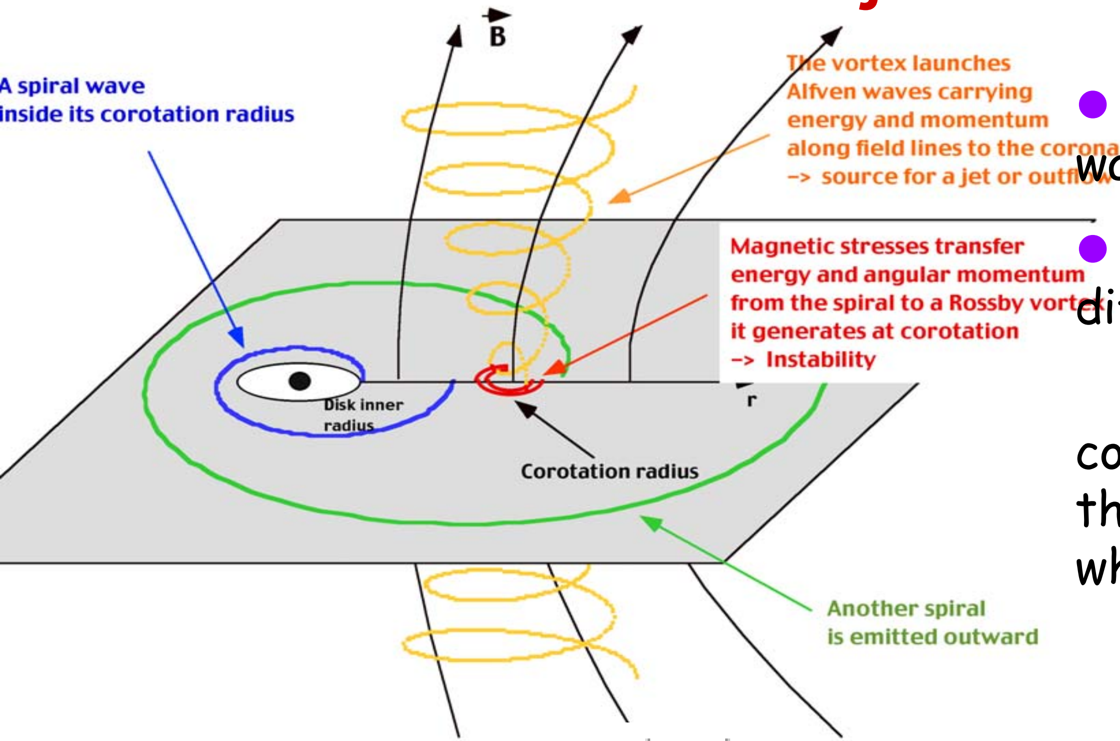
➔ large scale instability

spiral wave ~ galactic spiral but drivent by magnetic stresses instead of self-gravity

structure similar to the normal modes (= stationnary structure) of galaxies

All self-similar MHD jet model (Blandford & Payne, Pelletier & Pudritz, SMAE) are unstables

Accretion-Ejection Instability



- amplification by the outgoing wave ➔ small
- differential rotation + differential vorticity

➔ amplification by the coupling with a Rossby vortex (~ the great red spot of Jupiter) which it generates at its corotation.

- instability criteria: $\partial_s \ln\left(\frac{W\Sigma}{B_o^2}\right)$ has to be positive. $W=\kappa^2/(2\Omega)$

the gradients of W and Σ are stabilising and the one of B is distabilising.

➔ the spiral wave is amplified by extracting energy and angular momentum from the inner part of the disk (➔ accretion) and storing them into a Rossby vortex.

if there is a low density corona: the energy and angular momentum of the vortex are send toward the corona as Alfven waves.

Accretion-Ejection Instability (2)

- properties of the spiral:

  ➔ most unstable: the m=1 (one arm spiral) with $\omega \sim 0.1 - 0.3\ \Omega_{int}$ (rotation frequency at the inner edge of the disk).

  ↪ frequency similar to the Quasi-Periodic Oscillation of X-ray binaries

- if the disk has a low density corona

  ➔ energy and angular momentum of the vortex are transfered by Alfven wave toward the corona.

  ↪ power for a wind or a jet

with the WKB approximation we obtain the following contribution to the growth rate

$$\gamma_{Alfven} \approx -\frac{1}{2\tilde{\omega}^2 \beta^{1|2}} \kappa^2 \Omega \left(\frac{\rho_\infty}{\rho_o}\right)^{1|2}$$

➔ small (magnetic breaking) but diverge at the corotation (ω-mΩ=0) where is the Rossby vortex

↪ efficiency??

Code MHD-2D

- the perturbation is almost constante in the disk thickness
  ⇨ MHD-2D simulation is possible

- logarithmic grid ⇨ well adapted to the problem (denser for small r, and possibiliti to have a large diskS)

- physic similar to the galatic spirals ⇨ similar methods
  magnetic potential outside the disk $\vec{B} = \nabla\Phi_M$

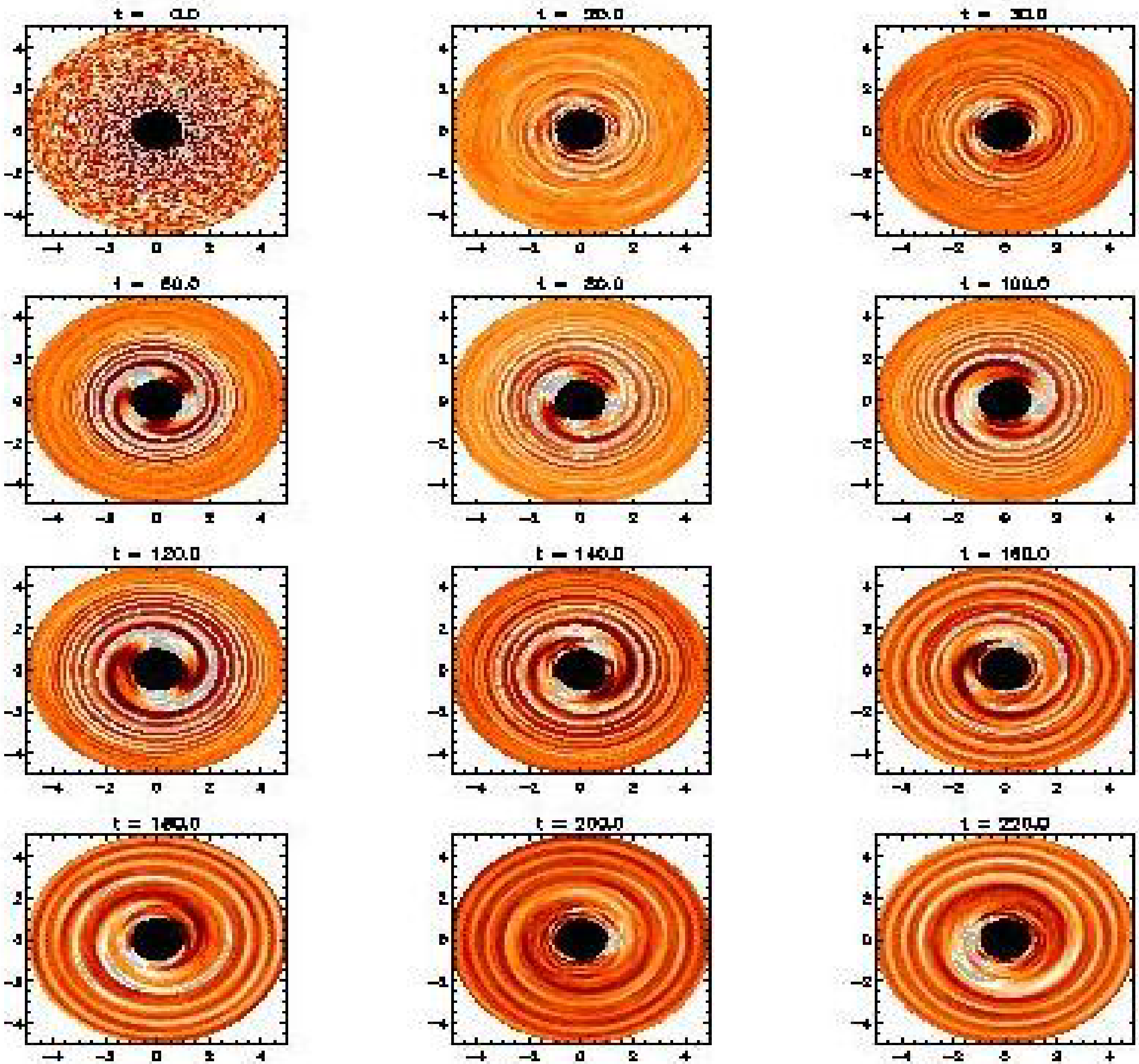
$$\Delta\Phi_M = -B_z\delta(z) \longleftrightarrow \Delta\Phi = 4\pi G\Sigma\delta(z)$$

$$\partial_t B_z + \nabla\cdot(B_z\vec{v}) = 0 \longleftrightarrow \partial_t\Sigma + \nabla\cdot(\Sigma\vec{v}) = 0$$

conservation of vertical magnetic flux — continuity

- use of the FARGO scheme (Masset 2000) :
  ➥ bigger timestep ⇨ faster computation

2.5D MHD Simulation



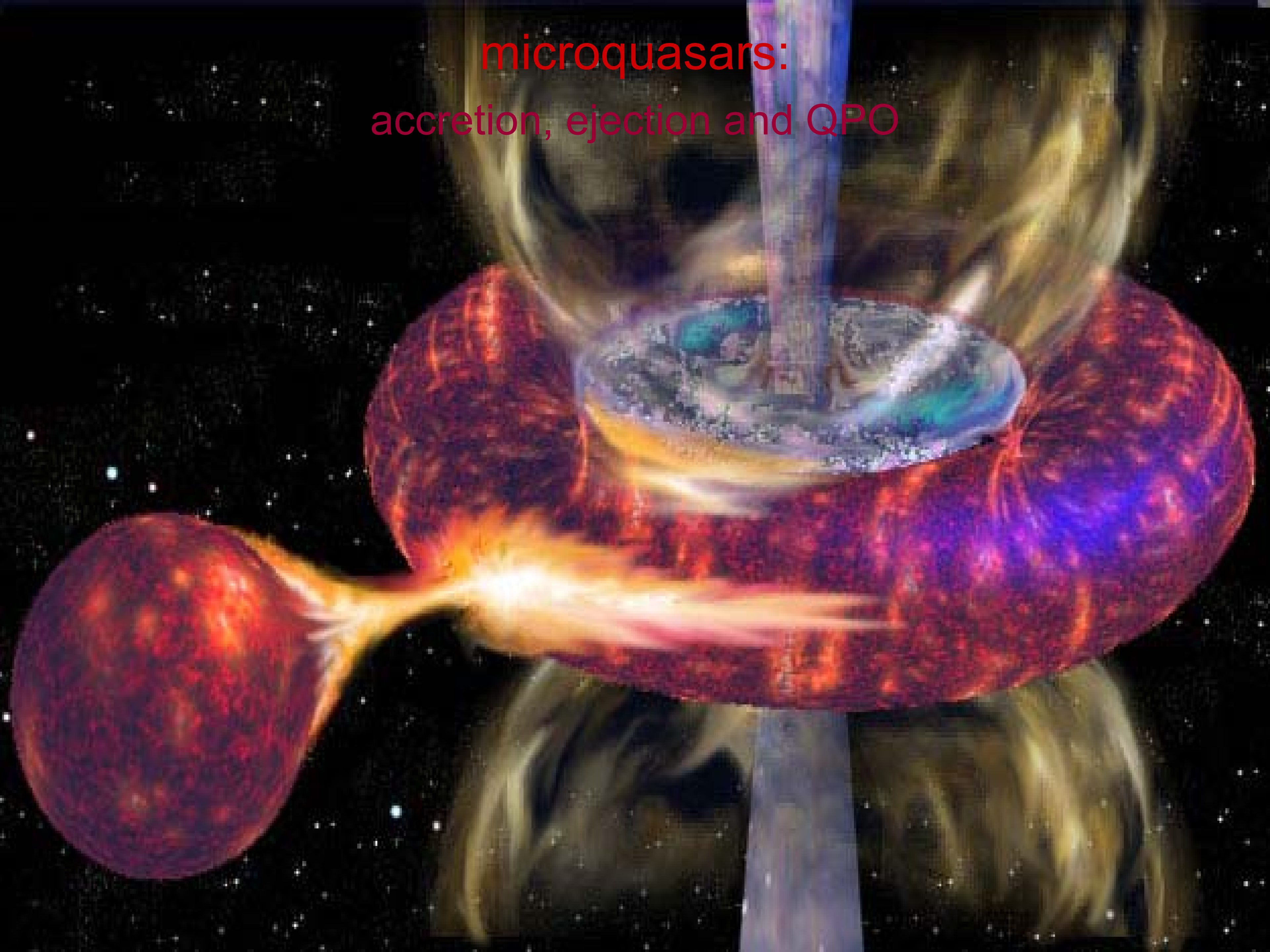
at the begining 3 arm (depending on the initial magnetic field strength), after 2 arms and at the end 1 arm spiral in the inner region of the disk

➲ good agreement with linear theory

Caunt & Tagger, 2001, A&A

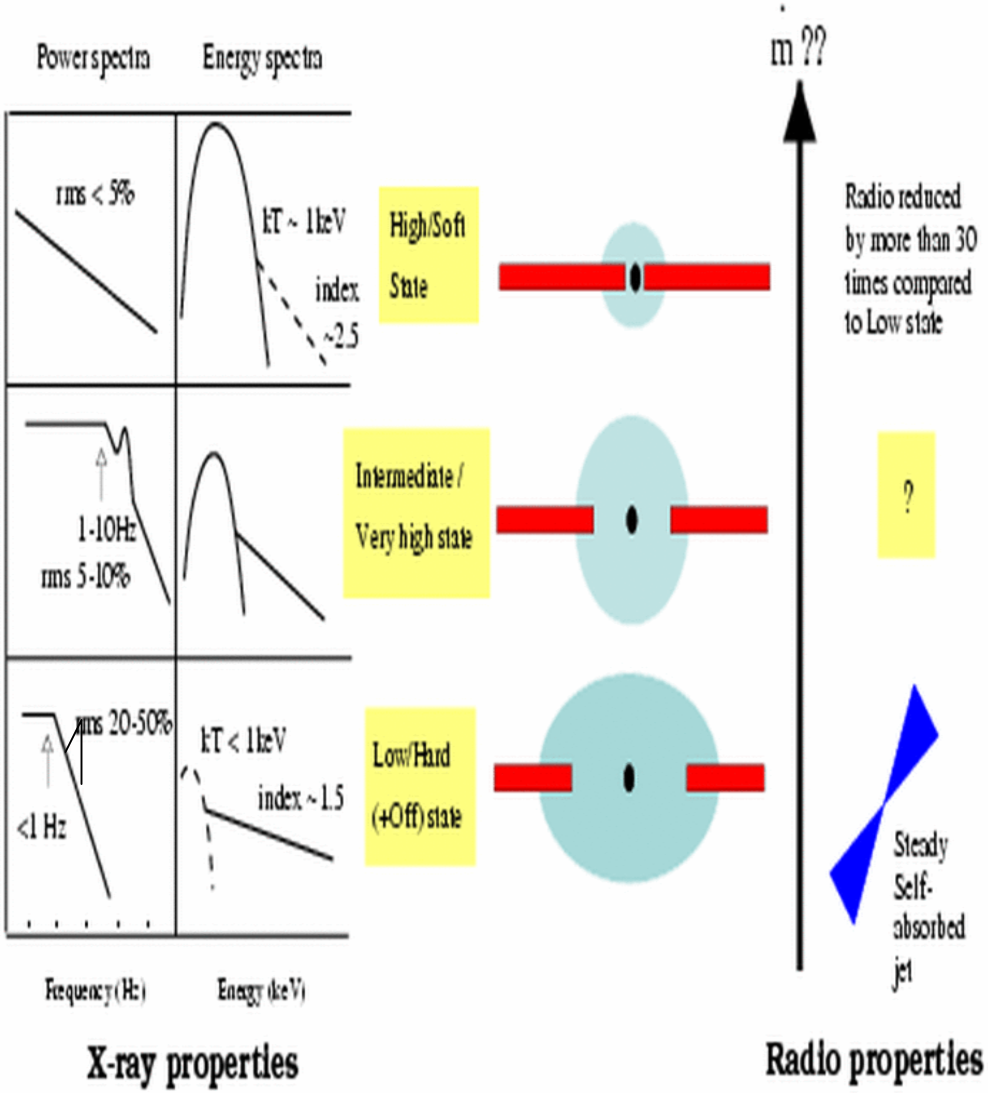
microquasars:

accretion, ejection and QPO



microquasars:

accretion, ejection and QPO



Fender

from the observations: several states

<u>high state</u>: the disk dominate the X-ray, no QPO no jet

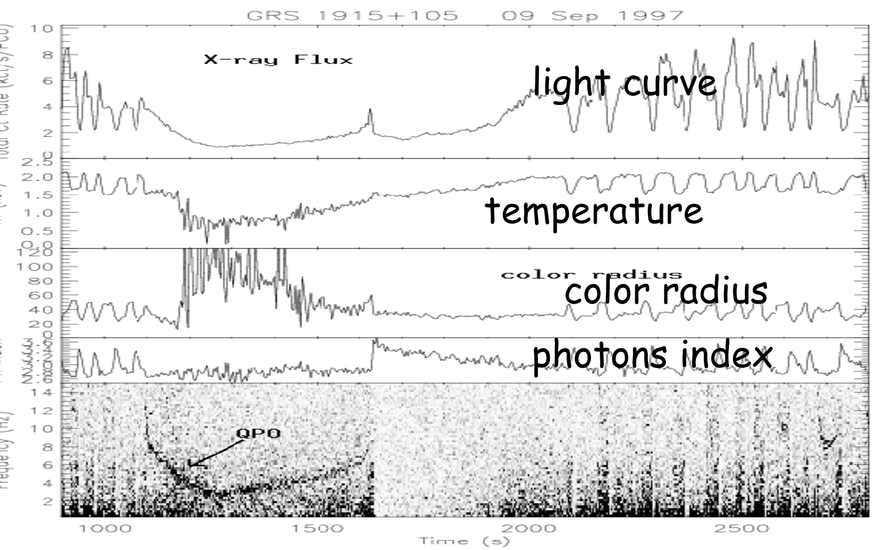
<u>low state</u>: the corona dominate, QPO and jet

<u>intermediate state</u>: courona + disk, QPO, jet ?

numerous observations (X-ray, radio, infra-red) and technics

➲ a lot of **constraint** on t theories

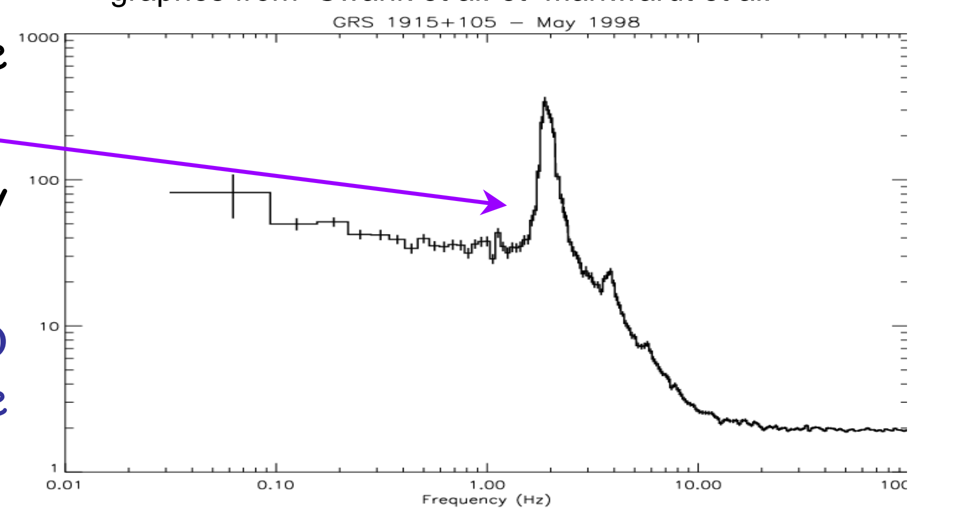
Observations



X-ray binaries (GRS 1915+105, GRO J1655-40,...) are observed on regularly basis by RXTE

From the spectral fits we obtain: the color radius (inner radii?), the temperature at the inner edge, ...

graphes from Swank et al. et Markwardt et al.



and with the Fourier Transform we obtain: Quasi-Periodic Oscillations (QPO)

we are interested in the low-frequency QPO (1-10 Hz)

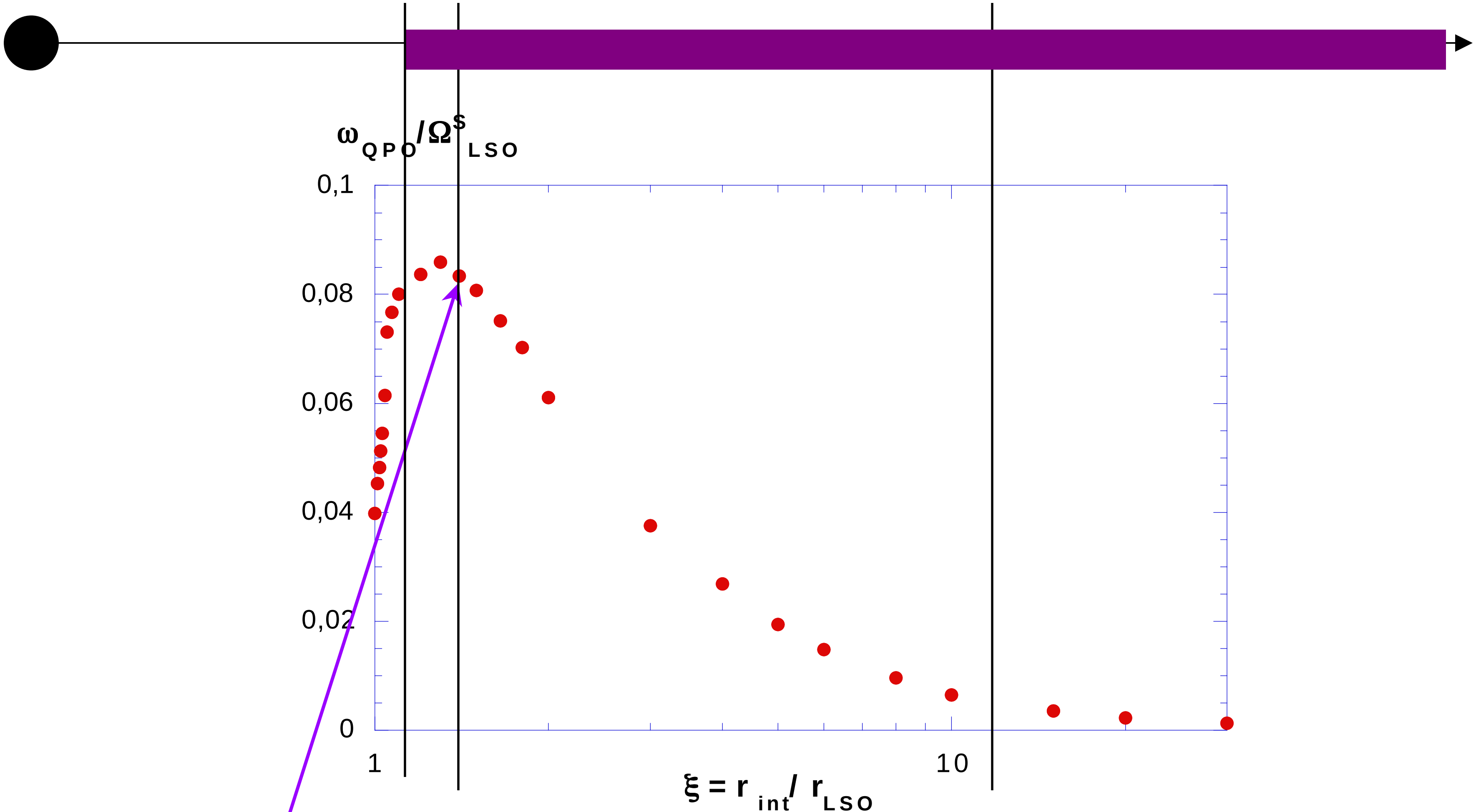
indeed the frequency of these QPO seems to follow the inner radii of the disk, as do the frequency from the AEI.

There exist several theoretical model for the low-frequency QPO (mainly two).
The AEI seems to be the best candidate.

IV. AEI and Observation

i. From AEI to QPO

AEI radius-frequency Correlation



the propagation cavity appears when $r_{int} < 1.4\, r_{LSO}$

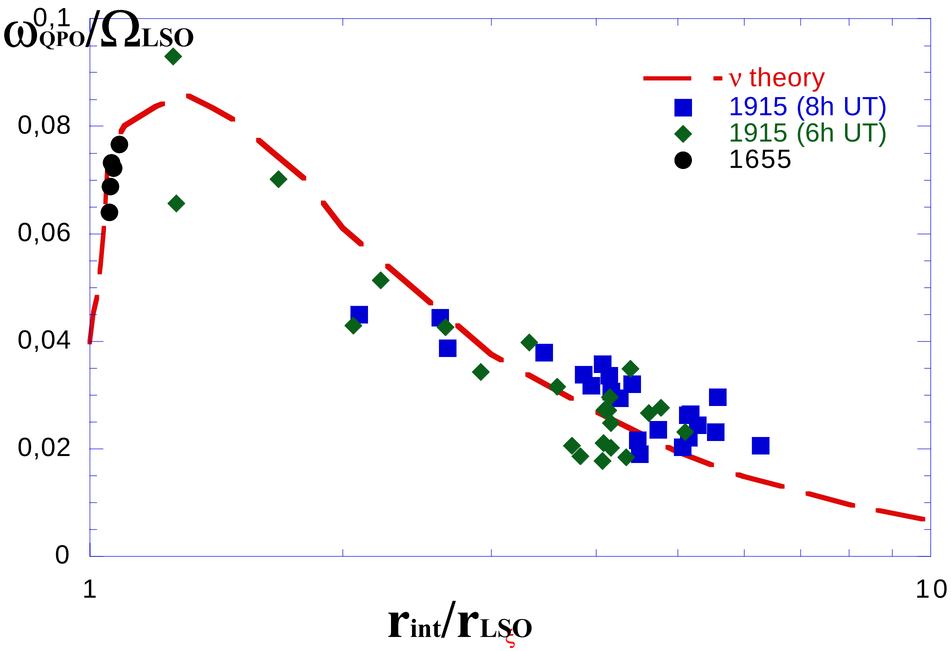
➥ important result: inversion of the slope for $r_{int} < 1.3\, r_{LSO}$

Comparison with Observations

in collaboration with Jérôme Rodriguez

When we obtained the correlation predict by the AEI

➔ new observations from GRO J1655-40 showed an inverted correlation of the QPO frequency as function of the radius compare with other X-ray binaries such as GRS 1915+105.



Simultaneously the MFR criteria (Merloni *et al.*) was a guide to know which point should be kept.

We had to reject points with a very small radius from GRO J1655-40 and two points from GRS 1915+105

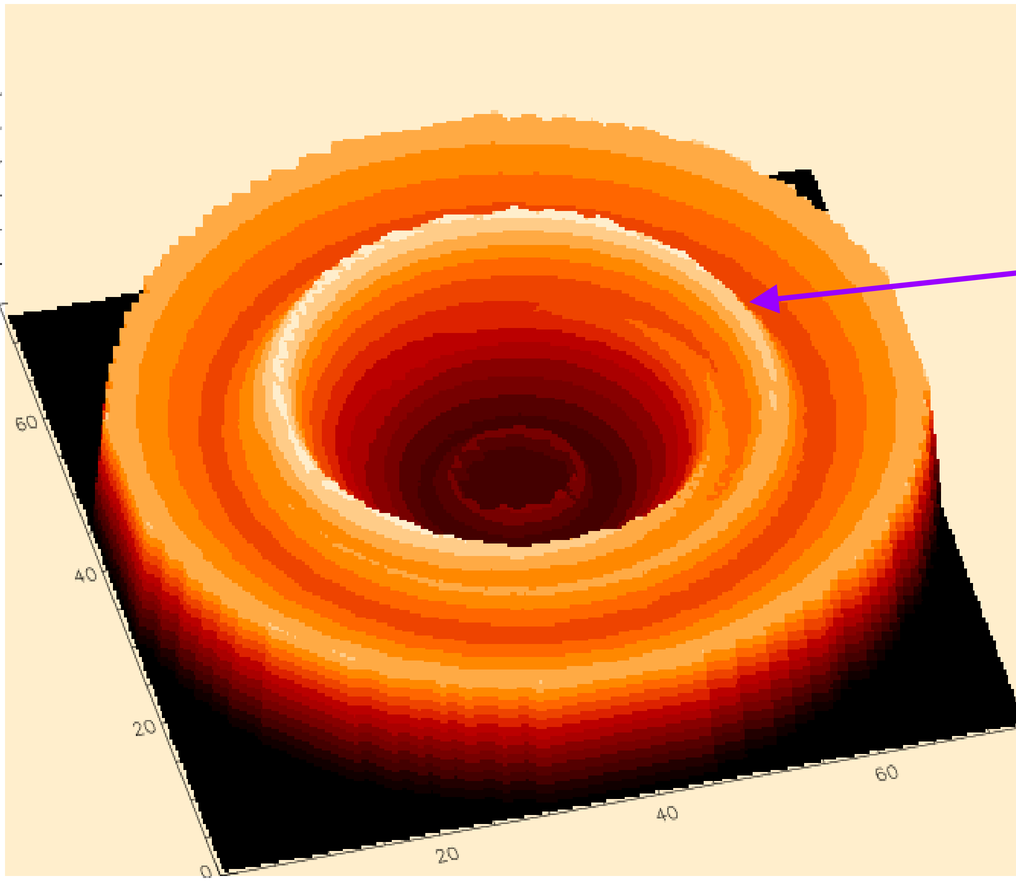
Even with a lot of approximations the fit result is good and give values for the mass and spin in agreement with independant results.

1km radii points of GRO J1655-40: emission is dominated by a hot points ?

From AEI to QPO*s*

in collaboration with M. Muno MIT/UCLA

the spiral shock in the disk create a hot-point and a local thickenning (hydrostatic equilibrium)



non linear MHD-2.5D simulation

➔ heating of the disk

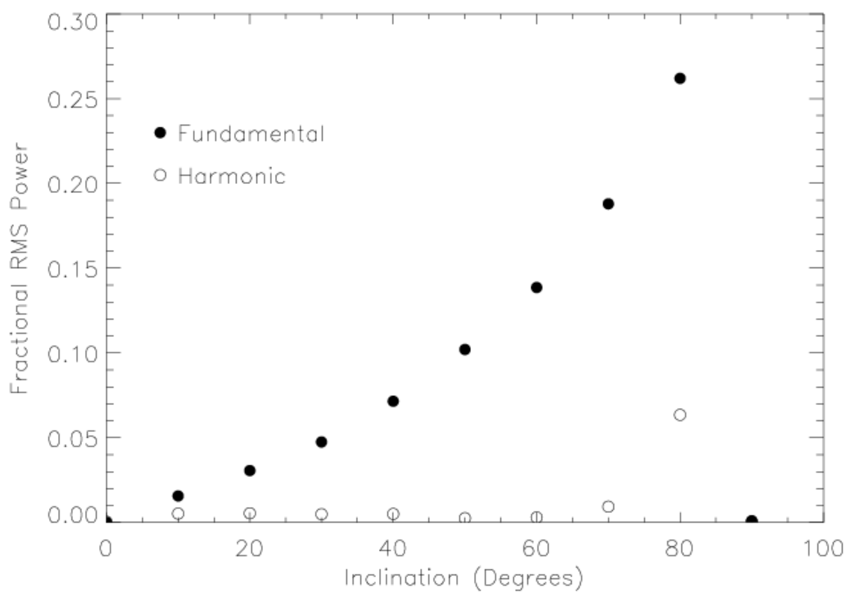
↳ simplified model for the disk thickenning

the computation of the X-ray emission of such an accretion disk **show a modulation of the X-ray flux** similar to the low-frequency QPO of X-ray binaries.

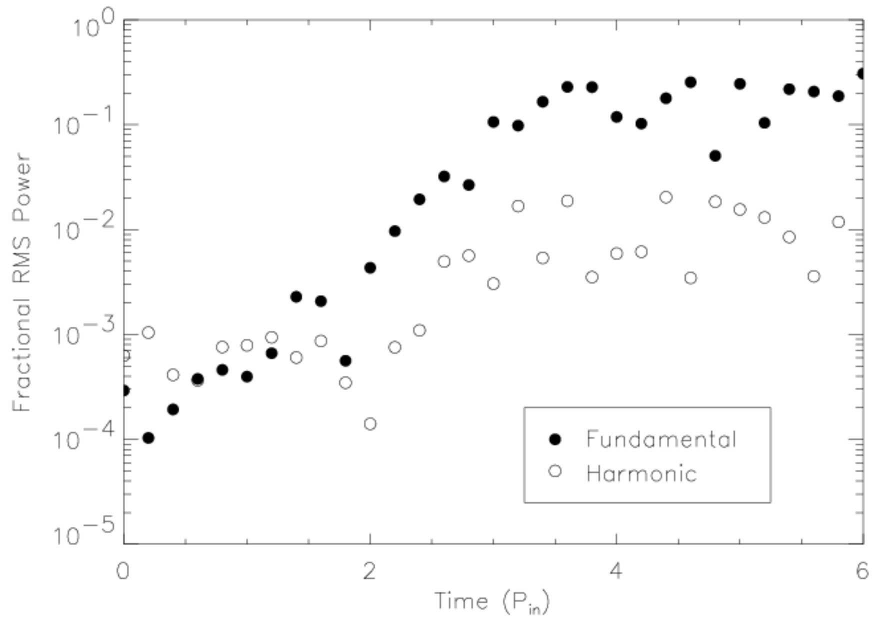
second step: synthetic light curve of QPO and impact on the iron line profile

AEI simulation and QPO

Some results from the modulation of the flux in the AEI simulation



rms amplitude of the QPO with respect to the inclination



time evolution of the rms amplitude

➔ more need to be done to compare with the observation
a space parameter study is on going

AEI: a model for QPO

- frequency between 1-10 Hertz
  - ➥ the frequency of the spiral wave $\omega \sim 0.1\text{-}0.3\ \Omega\mathrm{int}$ (rotation frequency at the inner edge of the disk)
- stability in time
  - ➥ large scale coherent structure as in galaxies
- rms amplitude rms as high as 20%
  - ➥ simulation more than 5% in a simple, underestimating, model
- correlation with the soft flux (disk)
  - ➥ comparison with observations
- QPO associated with a state where the power law (courona) dominate
  - ➥ accretion energy is not deposited localy (no heating of the disk)
- time lag changing sign, sub-harmoniques
  - ➥ possibilities of geometrical effect coming from the jet (in preparation)

IV. AEI and Observation

ii. Alfven waves emission

Alfven Wave Emission

The Rossby vortex twist the footpoint of the field line threading the disk. If the disk has a low density corona:

torsion ➔ propagation as Alfven Waves

➔ energy and angular momentum extracted from ther inner part of the disk wil be transfered toward the corona where it can power a wind or a jet

Fom jet observation we know that a large amount of the accretion energy is emited in the jet

➔ We have to compute the efficiency of the Alfven wave emission in order to compare with observation

Variationnal Form

to describe the system we used a variationnal form ➔

$$\int_{s_{min}}^{s_{max}} \alpha\tilde{\omega}^2(|\nabla_\perp\overline{\mathcal{Y}}|^2 - |\nabla_\perp\overline{\Phi}|^2)\, ds + 2\int_{s_{min}}^{s_{max}} \alpha\Omega\Omega'\, |\partial_s\overline{\Phi}|^2\, ds$$

$$+2m\int_{s_{min}}^{s_{max}} \partial_s(\alpha\tilde{\omega}\Omega)\, |\overline{\Phi}|^2\, ds - 2m\int_{s_{min}}^{s_{max}} \tilde{\omega}\partial_s(\alpha\Omega)\, |\mathcal{Y}|^2\, ds$$

$$+[\alpha\overline{\Phi}^\star(\tilde{\omega}^2\nabla_\perp\overline{\Phi} - 2\Omega\Omega'\partial_s\overline{\Phi})]_{s_{min}}^{s_{max}} - [\alpha\tilde{\omega}^2\overline{\mathcal{Y}}\nabla_\perp\overline{\mathcal{Y}}^\star]_{s_{min}}^{s_{max}}$$

$$+2i[m\alpha\Omega\Omega'\overline{\Phi}^\star\overline{\mathcal{Y}} - \alpha\tilde{\omega}\Omega(\overline{\mathcal{Y}}\nabla_\perp\overline{\Phi}^\star + \overline{\Phi}^\star\nabla_\perp\overline{\mathcal{Y}})]_{s_{min}}^{s_{max}}$$

$$-\int_{s_{min}}^{s_{max}}\int_d \Phi^\star\nabla_\perp^2\nabla^2\Phi\, dz\, ds - \int_{s_{min}}^{s_{max}} [\mathcal{Y}\partial_z\nabla_\perp^2\mathcal{Y}]_{z_{min}}^{z_{max}}\, ds \longrightarrow \text{Alfven wave flux}$$

F = energy of the wave

+ **i** (outgoing wave + coupling with the Rossby vortex

+ k_z Alfven wave)

imaginary term ⇨ amplification or damping of the wave

From this we obtain the Rossby-Alfven wave, i.e. wave propagating like Alfven wave but affected by the vorticity gradient

➔ propagation on just one side of the corotation

Alfven wave flux

Efficiency of the mecanism: we computed the ratio between the flux emitted toward the corona by the mean of Alfven wave and the energy taken form the inner region of the disk (flux deposited in the vortex

the Alfven wave flux is proportionnal to the one deposit in the Rossby vortex .

➔ we can compute the ratio between them

$$\frac{F_{Alfven}}{F_{disk}} \sim \left(\frac{\rho_{corona}}{\rho_{disk}}\right)^{1/2} \left(\frac{r}{h}\right)^{3/2}$$

typical aspect ratio for an X-ray binaries $h/r \sim 10^{-2}$

➔ $F_{Alfven}/F_{disk} \sim 1$ really efficient mecanism when the density becomes bigger than $\rho_{corona}/\rho_{disk} \sim 10^{-6}$

Toward 3D-MHD simulation

We have obtain **anatically** an efficient mecanism for transfer of angular momentum from the inner region of the disk toward the corona but a full non-linear 3D MHD simulations of the disk and its corona still remain to be done.

to have a better understanding of the jet launching and how it relate to the accretion disk and the instabilities occuring in it we need 3D MHD simulation of the all system.

➔ 3D MHD simulations are the way to go to match observations

Conclusions

We obtain results in analytical, numerical and observation

↳ the AEI is now a good candidate to explain the low frequency QPO pbserved in microquasars

↳ progress about the QPO profile and lag

↳ the transfert of energy and angular momentum toward the corona by the mean of Alfven waves is very efficient.

<u>work to be done</u>

↳ spectrum of the QPO at higher energy and comparision with observation

↳ MHD-3D simulation of the disk and corna to study the jet launching